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(58) Field of search
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(54) Wavelength stabilisation and output power regulation of semiconductor light sources

(57) A semiconductor light source (1), whose wavelength and preferably also its output power are stabilised in a highly precise manner in that the laser current (I_0) or a portion of the laser beam is modulated, is advanced through a wave selection filter (13) and, after detection, a control signal is provided to the semiconductor via a phase-sensitive amplifier (16) and a comparator (19). Wavelength stabilisation to 10^{-9} and output power regulation to better than 10^{-3} can be attained.

Fig. 3.

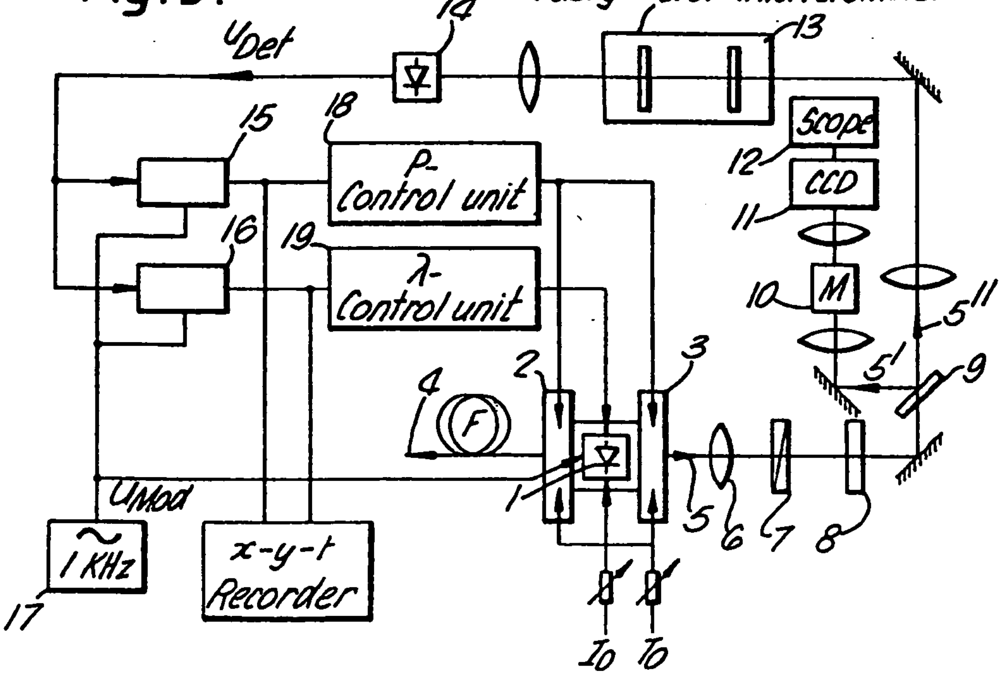

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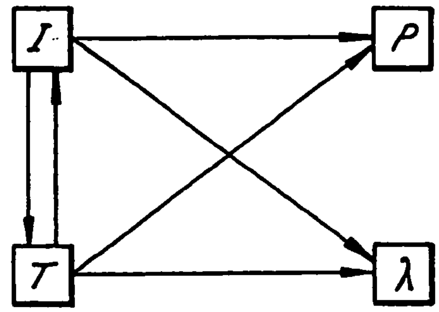
Fig.1.



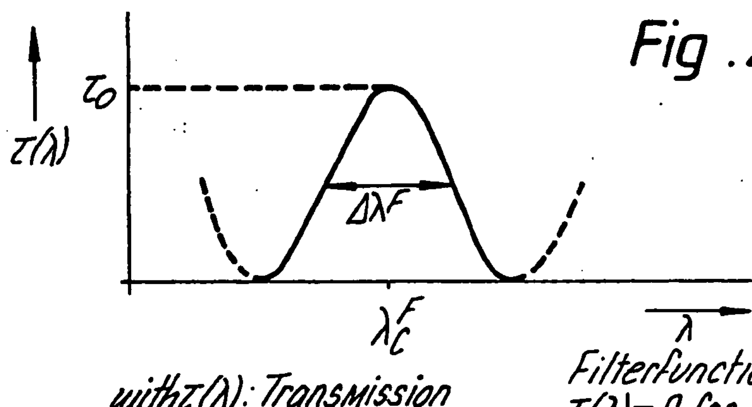


Fig.2a.

Filterfunction: $\tau(\lambda)$

$\tau(\lambda) = 0$ for $\lambda < \lambda_c^F - \Delta\lambda^F$

$\tau(\lambda) = 0$ for $\lambda > \lambda_c^F + \Delta\lambda^F$

$\tau(\lambda) = \frac{\tau_0}{2}\left[1 \pm \cos\left(\frac{\lambda - \lambda_c^F}{\Delta\lambda^F}\pi\right)\right]$

for $\lambda_c^F - \Delta\lambda < \lambda < \lambda_c^F + \Delta\lambda^F$

Fig.2b.

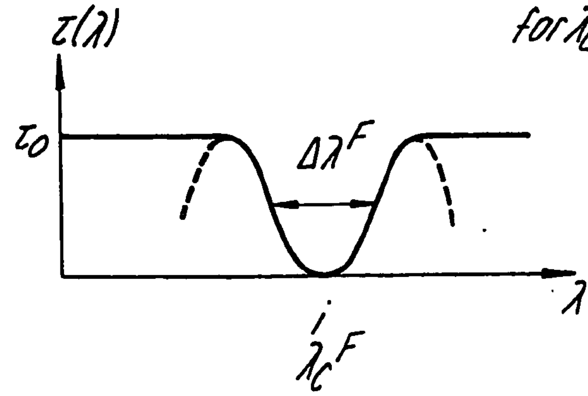


Fig. 3.

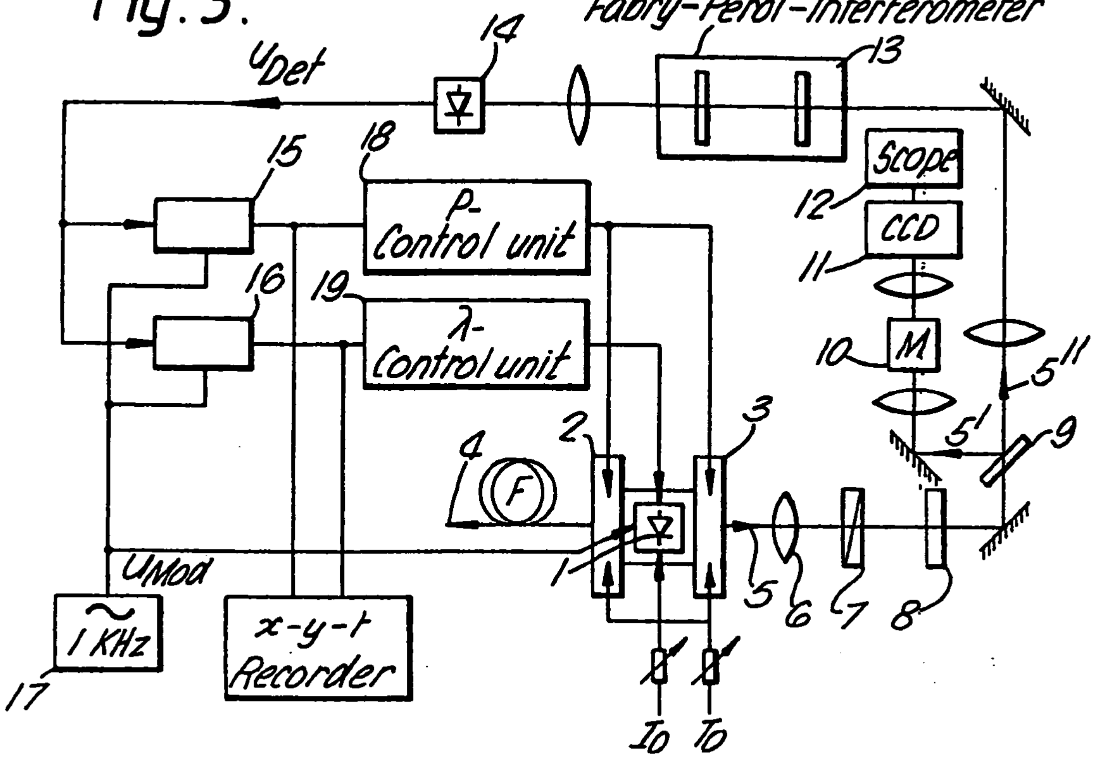


Fig. 4.

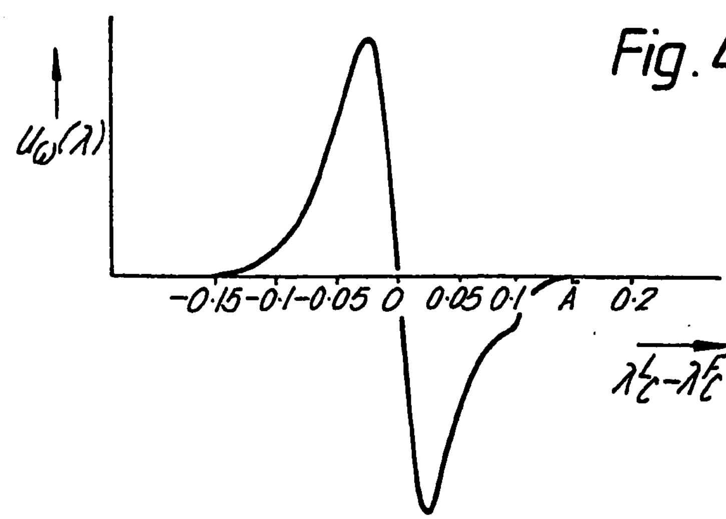


Fig. 5.

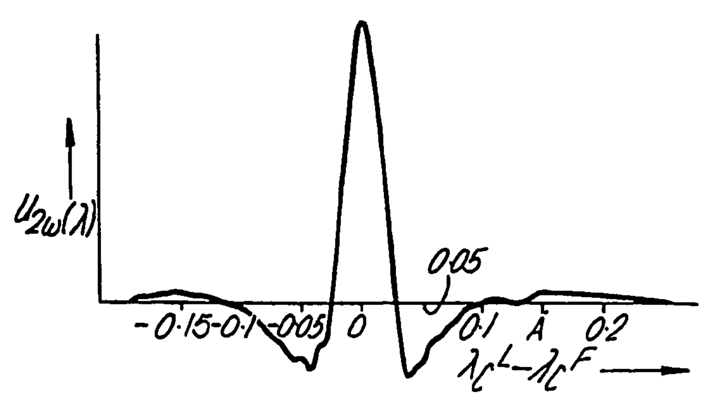


Fig. 6.

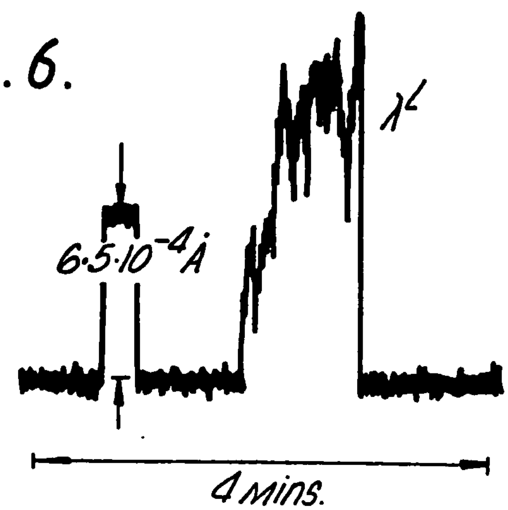

6·5·10⁻⁴Å
λᴸ
4 mins.

Fig .7.

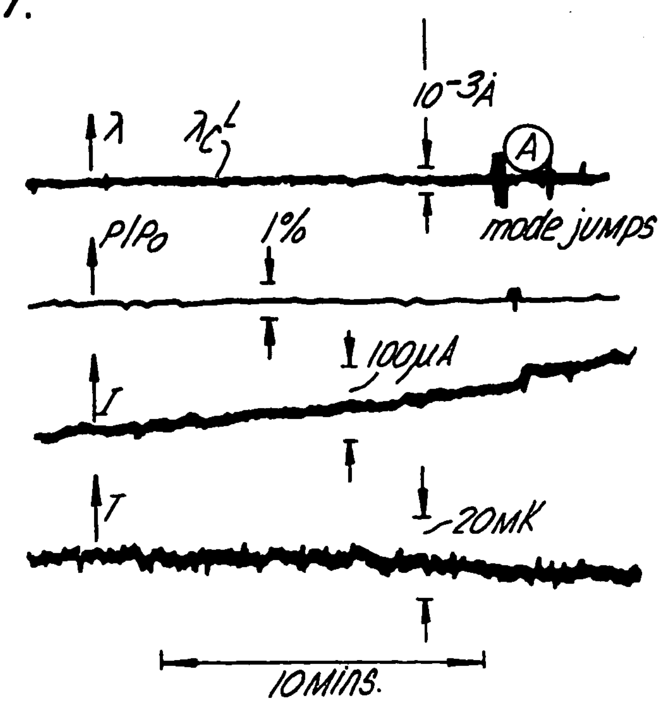

λ
λcᴸ
10⁻³Å
A
mode jumps
P/Po
1%
I
100μA
T
20mK
10mins.

Fig.8.

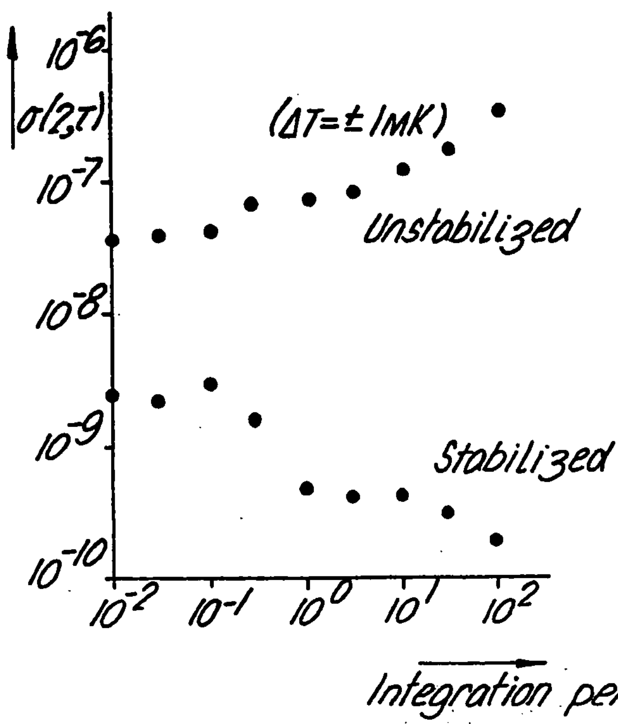


Fig. 9.

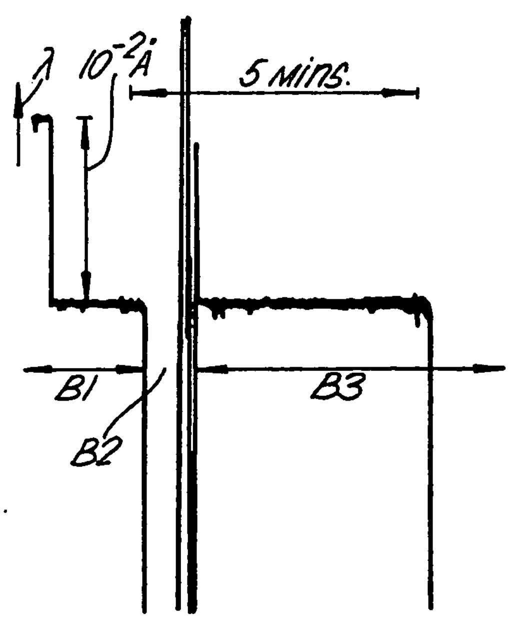


Fig. 10.

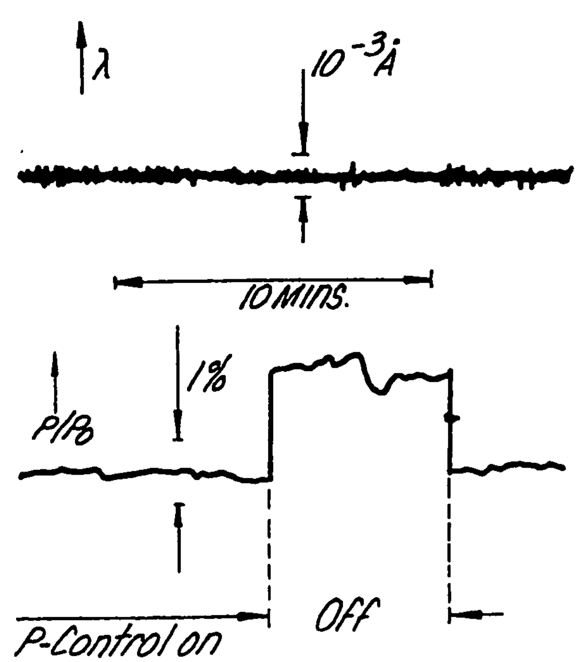
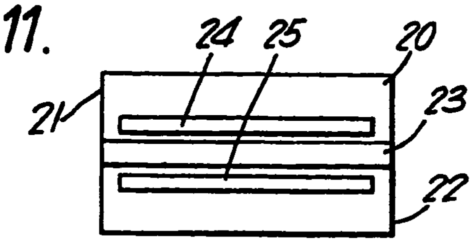


Fig.11.



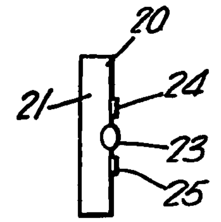


Fig.12.

Fig.13.

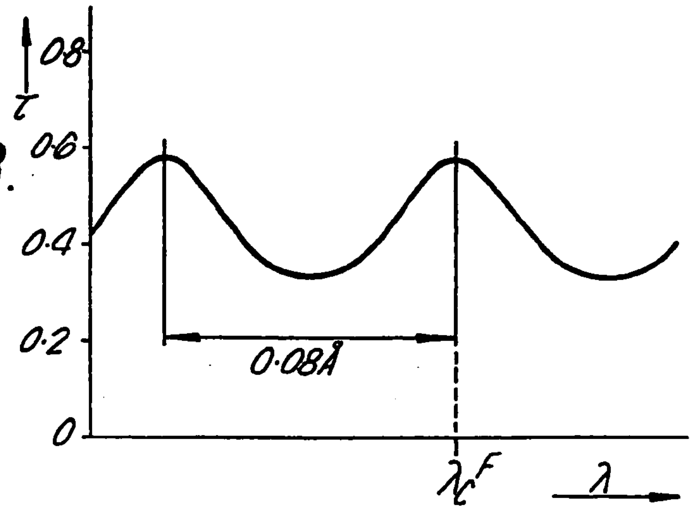
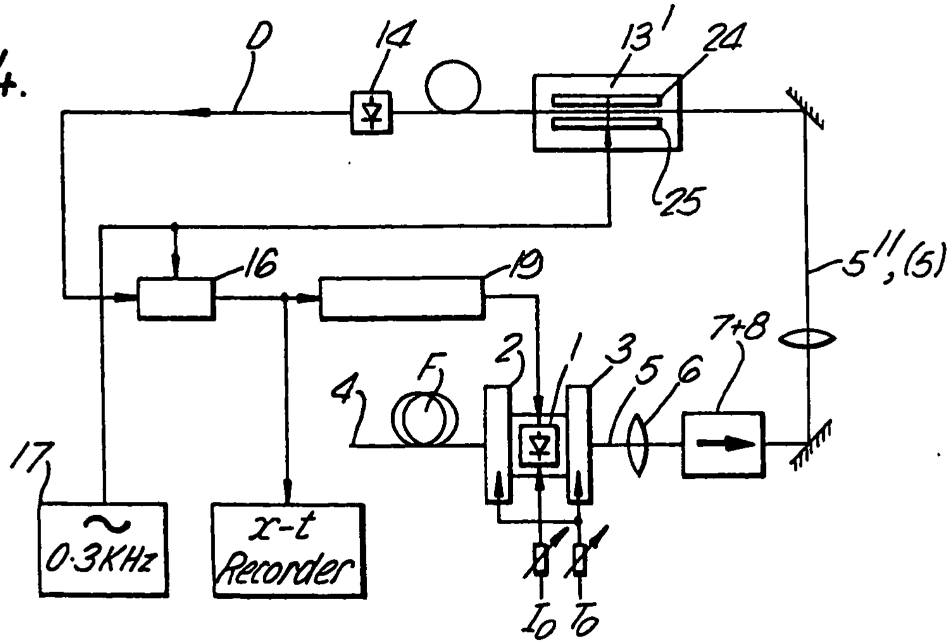


Fig.14.



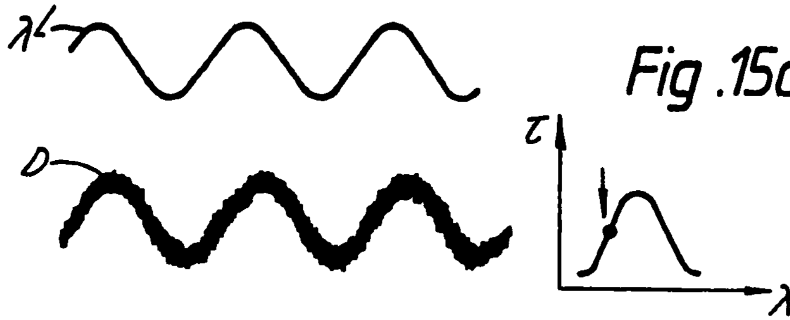


Fig. 15a.

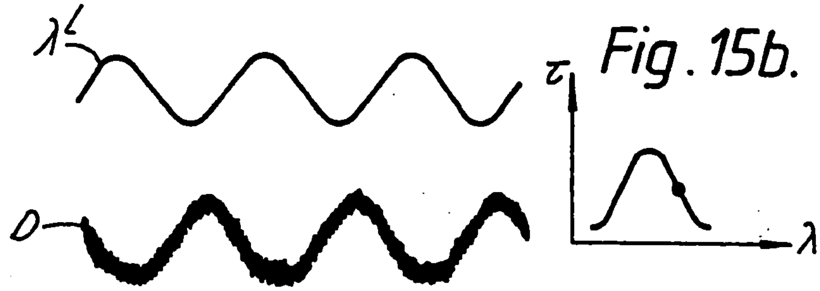


Fig. 15b.

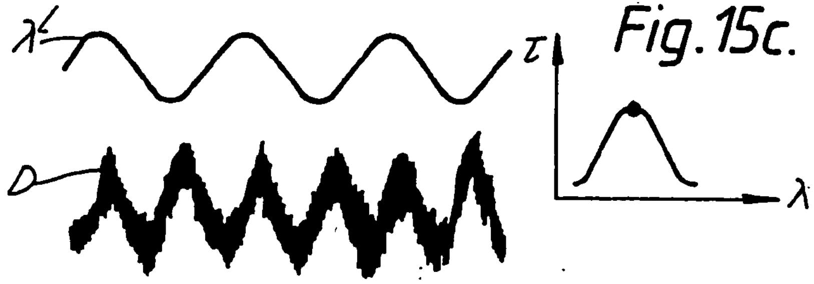


Fig. 15c.

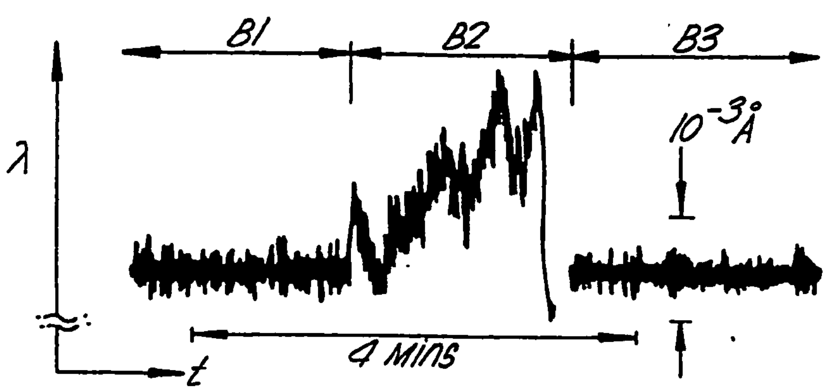


Fig. 16.

SPECIFICATION

Wavelength stabilisation and output power regulation of semiconductor light sources.

The present invention relates to a method of stabilising the wavelengths and regulating the output power of semiconductor light sources whose wavelength and output power are a function of injection current and the temperature of the semiconductor.

Spectral monitoring of longitudinal modes in transmitting means, such as semiconductor lasers or other semiconductor light sources, is playing an increasingly greater role in fibre sensor technology and in optical transmission systems with high data rates.

In order to accomplish this, it is necessary for the wavelengths of these transmitting means to be precisely measured and stabilised in accordance with particular requirements.

Prior art methods previously known from the literatature usually necessitate sophisticated equipment, as well as temperature stabilisation to $\leq 10^{-2}$ °Kelvin or less.

In this connection, wavelength constancies are achieved that are not sufficient for the sometimes high demands required in the case of the above-indicated technologies and systems.

Known from the magazine "Elektronik", No. 19, Sept. 23, 1983, page 30, is a C^3 laser diode, whose spectral line of emitted light can be tuned by 1 nm/mA through modification of the input current of the rear portion and by a total of 15 nm. Moreover, bonding the laser diode to a heat sink of copper is also known from this citation.

In addition, cooling a laser diode through an electrically operated chiller is known from European Disclosed Patent Publication No. 00 93 942, as temperature constancy has a significant impact on wavelength constancy.

The method of the present invention seeks to maintain the wavelength and, if desired, the output power of the light emitted from a semiconductor light source at a constant level with a high degree of accuracy for an extended period of time. In this connection, it should preferably also be possible to provide temperature constancy with a low degree of sophistication. It should also be possible to achieve this without requiring accurate temperature stabilisation.

According to a first aspect of the invention there is provided a method of stabilising the wavelengths and regulating the output power of a semiconductor light source whose wavelength and output power are a function of injection current and the temperature of the semiconductor, characterised in that the injection current is modulated by means of a modulation voltage and the modulated light contains the fundamental wave and high harmonic of the modulation frequency, a portion of the light emitted from the light source is advanced through a wavelength selective filter whose maximum absorption or maximum transmission is located within the range of the centre wavelength of the light source, a measurement signal is recovered by optoelectronic means from any shift in the centre wavelength of the light source from the centre wavelength of the filter, and the measurement signal contains the fundamental wave and higher harmonic of modulation voltage, the fundamental wave or odd harmonic of the measurement signal is processed with the fundamental wave or the corresponding uneven-numbered harmonic of the modulation voltage to form a first correction parameter, which is compared with an actual voltage in a first comparator and, depending upon the shift in the emitted centre wavelength from that of the filter, either a positive or a negative control voltage is generated by the first comparator and provided to the light source for controlling the injection current thereof, thereby regulating and/or stabilising the centre wavelength of the light source, the steady component or the second or a higher even harmonic of the measurement signal can, in addition, be simultaneously processed with the steady component of the portions of the light emitted from the light source or the second or the higher even harmonic of the modulaton voltage to form a second correction parmeter, and this correction parameter or a steady component of a measurement signal recovered in front of the filter is compared with a corresponding reference voltage in a second comparator, with a positive or a negative control voltage being generated by the second comparator and being provided to the light source for control of the temperature thereof, thereby regulating the output power of this light source.

According to a second aspect of the invention there is provided a method of stabilising the wavelengths and regulating the output power of a semiconductor light source whose wavelength and output power are a function of the injection current and the temperature of the semiconductor, characterised in that a portion of the light emitted from the light source is advanced through a light-wavelength-selective filter whose centre wavelength of the maximum absorption or maximum transmission is located within the range of the centre wavelength of the light source, and the phase and/or frequency of this portion is modulated by means of a modulator, a measurement signal is recovered by optoelectronic means from the shift in the centre wavelength of the filter relative to the centre wavelength of the light source and the measurement signals contains the fundamental wave and higher harmonic of the modulation voltage, the fundamental wave or uneven harmonic of the measurement signal is processed with the fundamental wave or the corresponding uneven harmonic of the modulation voltage to form

a first correction parameter, which is compared with an actual voltage, in particular a zero voltage, in a first comparator and, depending upon the shift in the emitted centre wavelength from that of the filter, either a positive or negative control voltage is generated by the first comparator and provided to the light source for controlling the injection current thereof, thereby stabilising the centre wavelength of the light source, the steady component or the second or a higher even harmonic of the measurement signal can, in addition, be simultaneously processed with the steady component of the portion of the light emitted from the light source or the second or the higher even harmonic of the modulation voltage to form a second correction parameter, and this correction parameter or a steady component of a measurement signal recovered in front of the filter is compared with a corresponding reference voltage in a second comparator, with a positive or a negative control voltage being generated by the second comparator and being provided to the light source for control of the temperature thereof, thereby regulating the output power of this light source.

These methods cover areas in which both low, as well as the highest, demands are placed on wavelength constancy. Moreover, a temperature constancy of only 0.1 Kelvin is required therefor, i.e. one power of ten less than in the case of the prior art. This represents a significantly reduced level of sophistication in conjunction with temperature stabilisation.

Moreover, the methods simultaneously permit output power stabilisation, without impairing wavelength constancy.

In addition, the space required for the necessary auxiliary means could, possibly, be much smaller than in the case of previous methods. Thus, practical application is possible both in sensor technology, as well as for optical transmission systems.

In order that the invention and its various other preferred features may be understood more easily, an embodiment thereof employing a semiconductor laser will now be described, by way of example only, with reference to the drawings, in which:–

Figure 1 shows schematically the interrelationship between the input and output parameters of a semiconductor light source;

Figure 2a is a response curve of a transmission filter as a function of wavelength,

Figure 2b is a response curve of an absorption filter as a function of wavelength,

Figure 3 is a schematic illustration of suitable control means for implementation of the method in accordance with the invention,

Figure 4 is a detector signal response curve at the modulation frequency as a function of the laser wavelength,

Figure 5 is a detector signal response curve at twice the modulation frequency as a function of the laser wavelength,

Figure 6 shows the laser centre wavelength as a function of time in the stabilised and unstabilised states,

Figure 7 shows the stability of the wavelength and of the output power of the laser and the corresponding changes in injection current and temperature over a period of approx. 20 minutes,

Figure 8 is a diagram of square roots from the Allan variance (2, T) in the stabilised and unstabilised states,

Figure 9 shows laser centre wavelength with various types of stabilisation, and

Figure 10 shows changes in the output power of the laser with laser stabilisation disabled,

Figure 11 is a top view of a phase modulator capable of being employed as an integrated optical Fabry-Perot interferometer,

Figure 12 is a side view of the phase modulator of Fig. 11,

Figure 13 is a filter response curve of the integrated optical Fabry-Perot interferometer,

Figure 14 illustrates schematically a stabilisation unit with an integrated optical Fabry-Perot interferometer,

Figures 15a to c show curves of detected signals at various operational statuses of the laser, and

Figure 16 shows the laser wavelength in the stabilised and unstabilised states.

The method according to the present invention can be implemented with light-emitting semiconductor lasers, such as: Monomode lasers, multimode lasers, superluminescence diodes. The semiconductor light sources all have the same characteristic input and output parameters, between which exist the interrelationships as will now be described with reference to Fig. 1.

In the arrangement of Fig. 1, modification of input current I modifies both the output power P, as well as the wavelength λ^L of the semiconductor laser in the same manner, i.e. if input current I is increased, wavelength λ^L will be shifted toward higher values, with output power P also being increased. Moreover, the temperature of the semiconductor is modified proportionately when input current I is modified. The temperature T of the semiconductor, in turn, is responsible for modification of the output power and of the wavelength of the semiconductor light source. It can thus be seen that it is possible for the wavelength and the output power to be maintained at a constant level by controlling the two input parameters. These interrelation-

ships can be described mathematically as follows:

$$(1)\quad d\lambda=\left(\frac{\partial\lambda}{\partial I}\right)_{eff}dI+\left(\frac{\partial\lambda}{\partial T}\right)_{eff}dT,\quad \left(\frac{\partial\lambda}{\partial I}\right)_{eff}=\left(\frac{\partial\lambda}{\partial I}\right)_{\Delta T=0}+\left(\frac{\partial\lambda}{\partial T}\right)\left(\frac{\partial T}{\partial I}\right)$$

$$\left(\frac{\partial\lambda}{\partial T}\right)_{eff}=\left(\frac{\partial\lambda}{\partial T}\right)_{\Delta I=0}+\left(\frac{\partial\lambda}{\partial I}\right)\left(\frac{\partial I}{\partial T}\right)$$

$$(2)\quad dP=\left(\frac{\partial P}{\partial I}\right)_{eff}dI+\left(\frac{\partial P}{\partial T}\right)_{eff}dT,\quad \left(\frac{\partial P}{\partial I}\right)_{eff}=\left(\frac{\partial P}{\partial I}\right)_{\Delta T=0}+\left(\frac{\partial P}{\partial T}\right)\left(\frac{\partial T}{\partial I}\right)$$

$$\left(\frac{\partial P}{\partial T}\right)_{eff}=\left(\frac{\partial P}{\partial T}\right)_{\Delta I=0}+\left(\frac{\partial P}{\partial I}\right)\left(\frac{\partial I}{\partial T}\right)$$

To implement stabilisation of the output parameters of the semiconductor laser, the laser may be modulated with a modulation voltage, or a portion of the laser light may be modulated by means of a suitable, electrically controllable filter, with corresponding measurement parameters and control parameters being generated from the modulation frequency with the aid of a wavelength-selective filter.

The modulated injection current of the laser and the laser light wavelength and laser output power generated therefrom can be described by the following mathematical equations:

$$(3)\quad I^L=I_0^L+\Delta I_A^L\cdot\sin\omega t$$

$$\longrightarrow$$

$$(4)\quad \lambda_L^L=\lambda_0^L+\Delta\lambda_A^L\cdot\sin\omega t$$

$$(5)\quad P^L=P_0^L+\Delta P_A^L\cdot\sin\omega t$$

I^L : Laser injection current
I_0^L : D.C. injection current
ΔI^L : Amplitude of the modulation current
λ_0^L : Laser steady wavelength component
λ_c^L : Laser centre wavelength
$\Delta\lambda$ Laser wavelength amplitude through modulation
P_0^L : Laser steady power component
ΔP_A^L : Laser output power amplitude through modulation

The filter curves of the wavelength-selective filters employed can be described in the form of trigonometric functions. As can be seen from Fig. 2a, the filter curve in the area of the centre wavelength of the filter λ_c^F can be viewed as being a cos function with a transmission filter, with the transmission satisfying the following formula during modulation:

$$(6)\quad \tau=\frac{\tau_0}{2}\left[1+\cos\left(\frac{\lambda_C^L+\Delta\lambda_A^L\sin\omega t-\lambda_C^F}{}\,\pi\right)\right]$$

τ_0 : Maximum filter transmission
λF : Filter centre wavelength
$\Delta\lambda F$: Filter bandwidth

Correspondingly, in the case of an absorption filter, whose filter curve is shown in Fig. 2b, the filter curve function can also be viewed as being a cos function, however with a negative sign. In the case of a transmission filter, zeroes are produced if the laser wavelength is shorter than the centre wavelength of the filter, less the filter bandwidth, or if the laser wavelength is longer than the centre wavelength of the filter, plus the filter bandwidth.

A method in accordance with the present invention will now be described with reference to Fig. 3, which shows the design principle and the circuitry of the possible practical example. A semiconductor light source, preferably designed in the form of a laser 1, in the practical example a GaAlAs semiconductor laser, has Peltier elements 2 and 3 arranged one on each side for temperature control. In the area of the forwardly emitted laser beam 4 or the rearwardly emitted laser beam 5, the Peltier elements have a corresponding hole, generated, for example, by means of a NdYag laser beam. Laser 1 can be set for the desired output power and wavelength by means of a controllable input current I_0. By means of Peltier elements 2, 3, the temperature of the laser is set to a required value and maintained at a constant level with an accuracy of 1×10^{-3} °Kelvin, for example.

Rearward laser beam 5 passes through a focussing lens 6, a polarisation filter 7 and a quarter wave plate 8, which prevent reflection back into laser 1. A portion 5′ of rearward laser beam 5 can be separated by means of a subsequent beam splitter 9. This partial beam 5′ is advanced via a grating monochromator 10 to an optical-electrical transducer 11, e.g. a light-sensitive diode line, which converts the optical signals into electrical signals. The latter can be viewed on a scope 12. By means of this arrangement, which is not, in itself, required for performance of the present invention, it is possible for laser 1 to be set for the desired wavelength without regulation and stabilisation when it is put into service for the first time, i.e. for the centre wavelength λ_c^L (fundamental mode) in the case of a monomode laser and for this or one of the adjacent modes in the case of a multimode laser or a superluminescence diode.

Beam 5″ passes through a Fabry-Perot interferometer 13, which is followed by a detector 14. The output of the latter is provided to a first and to a second phase-sensitive amplifier 15 and 16, which are known in the form of so-called lock-in amplifiers.

An LF generator 17 provides a modulation voltage U_{Mod} to laser 1 for modulation of laser beams 4, 5 and to the two phase-sensitive amplifiers 15 and 16, as a reference voltage. The output of first amplifier 15 is connected with a control unit 18 and that of second phase-sensitive amplifier 16 with a control unit 19, with each of the control units containing a comparator. Control unit 18 controls Peltier elements 2 and 3, while control unit 19 controls injection current I_0 of laser 1.

The procedure and the theory of operation of the individual devices is as follows:

After the device has been put into operation and the laser wavelength set as described above, modulation voltage $U_{Mod} = U_0 \sin \omega t$, generated by LF generator 17, is modulated with a frequency of 1 kHz of input current I_0, for example. This causes modification of centre wavelength ^{L} and of laser and output power P, in accordance with equations (4) and (5).

As a consequence of this modulation, an output signal appears at the output of Fabry-Perot interferometer 13 and, following detection by detector 14, at the latter; in addition to the steady component of laser beam 5″, the output signal also contains its harmonic. The detector signal can be developed mathematically in accordance with Bessel functions. In particular, the first terms thereof differ significantly, i.e. the fundamental wave or first harmonic off modulation voltage U_{Mod}, with a frequency of

$$(7) \quad U_\omega(\lambda) \sim P_0 \mathcal{T}_0 J_1\left(\frac{\Delta\lambda_A^L}{\Delta\lambda^F}\cdot\pi\right)\left(\sin\left(\frac{\lambda_C^L-\lambda_C^F}{\Delta\lambda^F}\cdot\pi\right)\right),$$

shown in Fig. 4, and twice the frequency or second harmonic,

$$(8) \quad U_{2\omega}(\lambda) \sim P_0 \mathcal{T}_0 J_2\left(\frac{\Delta\lambda_A^L}{\Delta\lambda^F}\cdot\pi\right)\left(\cos\left(\frac{\lambda_C^L-\lambda_C^F}{\Delta\lambda^F}\cdot\pi\right)\right),$$

shown in Fig. 5, with $I\nu$ representing the Bessel function νth order of the first type. Within the

range $|\lambda_c^L - \lambda_c^F| \to 0$, the filter curves can be viewed as being sin functions (Fig. 4) or cos functions (Fig. 5), respectively.

As can be seen from equation (9) and Fig. 4, the phase length of $U\omega(\lambda)$ in the area of centre wavelength λ_c^L of laser 1 is greatly dependent upon the momentary wavelength λ^L of laser 1, thereby making this term highly suitable for control adjustment and stabilisation of laser centre wavelength λ_c^L. This is accomplished by comparing $U\omega(\lambda)$ with the fundamental wave of modulation voltage U_{Mod} by means of amplifier 16 and control unit 19, contaning a comparator, with input current I_0 of laser 1 being readjusted by means of the positive or negative signal obtained. This shifts laser wavelength ^{L} toward centre wavelength λ_c^L, thus stabilising it.

As can be seen from equation (8) and Fig. 5, double modulation frequency $U_2\omega(\lambda)$ is virtually independent of laser wavelength λ^L in the case of minor variances of laser frequency ^{L} from filter centre wavelength λ_c^F.

This fact is utilised in order to regulate the output power of laser 1 with this component. In order to accomplish this, the component is inputted into amplifier 15 at double modulation frequency 2ω, with amplifier 15 regulating the output power of laser 1 by controlling the temperature thereof via Peltier elements 2 and 3 by means of phase comparison with the corresponding component of moulation voltage U_{Mod} sin 2 t via control unit 18.

In Fig. 6, the laser centre wavelength is shown over a period of 4 minutes. Calibration for determination of the measured parameters was performed at the first jump. The temperature was set precisely for 1 mK. As can be seen, an accuracy of approx. 10^{-9} (RMS) was achieved in controlling wavelength λ_c^L (wavelength of the GaAlAs laser employed approx. 83 nm).

Fig. 7 shows wavelength λ_c^L with the wavelength regulation means enabled, as well as the output power variance, i.e. the stability of the output power, as well as the modification of the total current of the laser required therefor (i.e. injection current and modulation current and regulating current) and the required change in temperature. A mode jump occurred in the indicated range A. In systems of this type, this can occur as a result of the fact that isolation is sometimes not complete, i.e. as a result of the fact that return reflection of rearward laser beam 5 to laser 1 is not totally prevented.

The Allan variance shown in Fig. 8 shows clearly that, in the stabilised state, noise reduces over the integration period, i.e. the variation of the laser centre wavelength becomes smaller, and that, in the unregulated state, noise increaes, in spite of a temperature constancy of $\pm$ 1 mK.

Applications are also possible in which wavelength stabilisation is sufficient, and only minor demands are placed upon output power stability. In view of this aspect, the influence of wavelength stabilisation was performed experimentally under various conditions and is shown in the diagram contained in Fig. 9. In range B1, the laser wavelength was stabilised, with the temperature of laser 1 being kept at a constant level of 1 mK. The steep initial slope again shows calibration of the measurement. In range B2, λ^L stabilisation was disabled. As a consequence, a significant change in the laser wavelength is obtained. In range B3, λ^L stabilisation was enabled and temperature stabilisation was disabled. As can be seen, good wavelength stabilisation was obtained immediately again.

And Fig. 10, finally, shows that, even with output power stabilisation disabled, the change in output power over time amounts to less than 1%. The reason for this is that both input parameters of laser 1, wavelength and temperature, shift in the same direction, i.e. a higher injection current produces a higher wavelength and output power. A higher temperature produces both a lower wavelength, as well as lower output power.

Since, in most applications in which it is necessary to stabilise both wavelength as well as output power, the utmost value is placed upon wavelength constancy, the control period constant of wavelength stabilisation will be selected lower than that of output power stabilisation in these cases, in particular. In the practical example, the acting time constant for wavelength stabilisation amounted to 40 msec, while that for output power stabilisation amounted to 4 sec.

As described and illustrated, it is possible to obtain both wavelength and output power stabilisation simultaneously with simple means. In this connection, output power stabilisation of better than 10^{-3} was obtained, and the square root from the Allan variance amounted to 2.10^{-9} with an integration period of 30 msec and 2.10^{-10} with an integration period of 10 sec.

A Fabry-Perot interference filter was employed as the transmission filter. Since a customary design of this nature necessitates a great deal of space, means for implementing the method according to the present invention can not be employed in many cases because of space limitations. Other suitable filters can be substituted for the Fabry-Perot interferometer, for example an integrated optical Fabry-Perot interferometer or filters operating on the basis of rare earths or filters with an optical-galvanic effect.

The same advantages as those described above can also be attained if a controllable absorption or transmission filter is employed instead of modulation of the laser current. Filters of this type are known. Thus, for example, a Fabry-Perot interferometer can be controlled by means of piezo elements. Moreover, filters are also known whose [illegible]

an electrical voltage applied to two or more electrodes. In these cases, only partial laser beam 5″ is modulated. This provides the advantage that laser 1, itself, is not influenced by the modulation.

The recitations also illustrate that sufficiently accurate wavelength constancy is obtained, even if the temperature is only stabilised within 1 K. It is merely necessary to ensure that the temperature constancy is selected in such a manner that no mode jump occurs.

The present invention is employed primarily in fibre sensors, for example in a fibre gyro, or in optical transmission systems, for example wavelength multiplex systems or coherent transmission methods.

Wavelength stabilisation with a controllable wavelength selection filter, employing an integrated optical Fabry-Perot interferometer shown in Figs. 11 and 12, will now be described below. The integrated optical Fabry-Perot interferometer comprises a substrate plate 20 of lithium niobate, whose end surfaces 21, 22 are ground and polished plane and parallel one to the other. A strip 23, acting as an optical resonator, is formed by diffusing titanium dioxide into substrate plate 20. Two electrodes 24, 25 are provided on either side of strip 23 and parallel thereto; when a control voltage is applied to electrodes 24, 25, the resonator frequency can be modified as a result of the change in the refraction index. A design of this nature is a known phase modulator. According to the present invention, it is employed here as a controllable Fabry-Perot interferometer. Through additional application of dielectric layers on end surfaces 21 and 22, the degree of reflection can be increased and the quality of the resonator enhanced. However it has been found that the quality of the resonator without dielectric layers is sufficient for obtaining the desired effect according to the present invetion. Thus, it is possible to obtain a relatively cost-efficient, very small Fabry-Perot interferometer, thereby enabling very compact, highly stabilised laser modules to be fabricated, which permits their practical employment in fibre transmission and sensor systems. This phase modulator acts in the same manner as a transmission filter, as a function of the laser wavelength. However, in this case, there is a periodic transmission repetition with continuous wavelength. Since the phase modulator employed was not provided with dielectric layers, the quality thereof is not as great as in the case of the Fabry-Perot interferometer described at the outset. A filter curve having a relatively high steady component is obtained. This curve can be described by means of the following mathematical relationship:

$$(9) \quad \tau(\lambda) = \tau_{max}\left(1 + \frac{4R}{(1-R^2)} \cdot \sin^2\left(\frac{2\pi}{\lambda_c^L} \cdot n_{LiNbO_3} \cdot L\right)\right)^{-1}$$

λ_c^L : Laser centre wavelengh
L : Resonator length
R : Output power reflection coefficient of PM
τ max : Maximum transmission of PM

Assuming a Fresnel reflection of 0.14 and a waveguide attenuation of 0.5 dB/cm, a transmission curve of the type shown in Fig. 12, for example, is obtained, which coincides relatively well with the actual measurement. By applying above-indicated sinusoidal modulation voltage U_{Mod} to electrodes 24 and 25, periodic modification of the filter centre wavelength is obtained.

$$(10) \quad \lambda_C^F = \lambda_0 + \Delta\lambda_A^L \sin\omega t$$

λ_0^F : Steady filter wavelength component
λ_A^F : Wavelength amplitude

The design of the schematic diagram of a stabilisation unit shown in Fig. 14 is similar to that shown in Fig. 3, and the theory of operation is, in principle, also the same. The only difference is that integrated optical Fabry-Perot interfermeter 13′ has been substituted for a customary Fabry-Perot interferometer. Although output power regulation by means of Peltier elements 2 and 3 with the aid of a steady component or the second harmonic or a higher even-numbered harmonic has not been performed experimentally, it is just as possible as in the case of the above-described practical example.

Figs. 15a to c show the curve of the signal D detected and outputted by detector 14. In Fig. 15a, the wavelength centre frequency of the laser light is lower than that of phase modulator 20, or controllable Fabry-Perot interferometer 13′; in Fig. 15b, it is higher; and in Fig. 15c, both are exactly the same. As can be seen, in the case of Fig. 15a, signal D is positive relative to modulation voltage U_{Mod} of modulator 17, and control unit 19 outputs a negative correction parameter; in the case of Fig. 15b, signal D is negative, thereby causing control unit 19 to output a positive correction parameter; and in the case of Fig. 15c, the fundamental frequency component of modulation voltage U_{Mod} disappears entirely. Instead, signal D occurs especially clearly, in particular with twice the modulation frequency, as the curvature of the filter curve is greatest at the maximum, and the harmonics, especially the second harmonic, attain higher values. However this component with the double modulation frequency is not recognised as being a control signal or filtered out by phase detector 16 and control unit 19; consequently, no correction parameter is outputted in this case. However, just as described on the basis of Fig. 3, the detected second harmonic could also be employed for output power regulation.

Shown in Fig. 16 is the stabilisation of the laser wavelength achieved with the phase modulator serving as an integrated optical Fabry-Perot interferometer. Ranges B1 and B3 show the stabilised state, while range B2 shows the unstabilised state. Thus, the desired laser wavelength was able to be attained again with a constancy of up to 10^{-9} immediately after the stabilisation was enabled.

The detection method according to the present invention employed for wavelength stabilisation can also be employed for measurement of the half-wave voltage and/or waveguide attenuation of integrated optical phase modulators. For this purpose, the phase modulator to be measured is employed instead of interferometer 13 or 13′, for example, with a suitable, alterable voltage being applied thereto. Thus the voltage required for obtaining a phase shift of π can be determined in a simple manner.

Once again, the characteristic curves shown in Figs. 4 and 5 are obtained as the measurement and, possibly, control parameters.

In measuring waveguide attenuation, it is assumed that the reflection properties of the phase modulator as a result of Fresnel reflecton are known. A change in the filter curve shown in Fig. 2a or Fig. 13 is then only a parameter of the attenuation of the phase modulator. The steeper the slopes and the lower the steady component, the lower the attenuation.

The laser wavelength can be viewed as being constant for the period of this measurement, as the parameters to be measured generally and need not be measured with an accuracy of 10^{-9}.

However the wavelength of the laser light can additionally be stabilised in accordance with the method according to the present invention. In this case, the integrated optical phase modulator to be measured is then provided in addition to Fabry-Perot interferometer 13 or an integrated optical phase modulator 13′ employed as one. In this case, the Fabry-Perot interferometer intended for control of the laser wavelength is provided in rearward beam 5 or 5″ and the integrated optical phase modulator to be measured is arranged in a partial beam branched off in front of the Fabry-Perot interferometer by means of a beam splitter or in forwardly emitted beam 4.

CLAIMS

1. A method of stabilising the wavelengths and regulating the output power of a semiconductor light source whose wavelength and output power are a function of injection current and the temperature of the semiconductor, characterised in that the injection current is modulated by means of a modulation voltage and the modulated light contains the fundamental wave and higher harmonic of the modulation frequency, a portion of the light emitted from the light source is advanced through a wavelength selective filter whose maximum absorption or maximum transmission is located within the range of the centre wavelength of the light source, a measurement signal is recovered by optoelectronic means from any shift in the centre wavelength of the light source from the centre wavelength of the filter, and the measurement signal contains the fundamental wave and higher harmonic modulation voltage, the fundamental wave or odd harmonic of the measurement signal is processed with the fundamental wave or the corresponding uneven-numbered harmonic of the modulation voltage to form a first correction parameter, which is compared with an actual voltage in a first comparator and, depending upon the shift in the emitted centre wavelength from that of the filter, either a positive or a negative control voltage is generated by the first comparator and provided to the light source for controlling the injection current thereof, thereby regulating and/or stabilising the centre wavelength of the light source, the steady component or the second or a higher even harmonic of the measurement signal can, in addition, be simultaneously processed with the steady component of the portion of the light emitted from the light source or the second or the higher even harmonic of the modulation voltage to form a second correction parameter, and this correction parameter or a steady component of a measurement signal recovered in front of the

positive or a negative control voltage being generated by the second comparator and being provided to the light source for control of the temperature thereof, thereby regulating the output power of this light source.

2. Amethod of stabilising the wavelengths and regulating the output power of a semiconductor light source whose wavelength and output power are a function of the injection current and the temperature of the semiconductor, characterised in that a portion of the light emitted from the light source is advanced through a light-wavelength-selective filter whose centre wavelength of the maximum absorption or maximum transmisssion is located within the range of the centre wavelength of the light source, and the phase and/or frequency of this portion is modulated by means of a modulator, a measurement signal is recovered by optoelectronic means from the shift in the centre wavelength of the filter, relative to the centre wavelength of the filter relative to the centre wavelength of the light source and the measurement signal contains the fundamental wave and higher harmonic of the modulation voltage, the fundamental wave or uneven harmonic of the measurement signal is processed with the fundamental wave or the corresponding uneven harmonic of the modulation voltage to form a first correction parameter, which is compared with an actual voltage, in particular a zero voltage, in a first comparator and, depending upon the shift in the emitted centre wavelength from that of the filter, either a positive or negative control voltage is generated by the first comparator and provided to the light source for controlling the injection current thereof, thereby stabilising the centre wavelength of the light source, the steady component or the second or a higher even harmonic of the measurement signal can, in addition, be simultaneously processed with the steady component of the portion of the light emitted from the light source or the second or the higher even harmonic of the modulation voltage to form a second correction parameter, and this correction parameter or a steady component of a measurement signal recovered in front of the filter is compared with a corresponding reference voltage in a second comparator, with a positive or a negative control voltage being generated by the second comparator and being provided to the light source for control of the temperature thereof, thereby regulating the output power of this light source.

3. A method as claimed in claim 1 or 2, characterised in that a Fabry-Perot interferometer is employed as the wavelength-selective filter.

4. A method as claimed in claim 1 or 2, characterised in that a rare-earth absorption filter is employed as the wavelength-selective filter.

5. A method as claimed in claim 1 or 2, characterised in that an absorption filter operating in accordance with the optical-galvanic effect is employed as the wavelength selection filter.

6. A method as claimed in claim 4 or 5, characterised in that the absorption filter is a controllable filter.

7. A method as claimed in any one of claims 1, 3, 4, 5 or 6, characterised in that the rearwardly emitted beam of a modulated laser is employed for measurement and stabilisation.

8. A method as claimed in any one of claims 2 to 6, characterised in that the rearwardly emitted beam of a laser is modulated and employed for measurement and stabilisation.

9. A method as claimed in any one of claims 1 to 8, characterised in that a portion of the rearwardly emitted beam of a laser is masked prior to entering the wavelength-selective filter and advanced to a scope which is employed for at least initially setting the centre wavelength of the laser with the stabilisation disabled.

10. A method as claimed in claim 9, wherein the centre wavelength of the laser is intially set.

11. A method as claimed in any one of claims 1 to 10, characterised in that a control unit is employed for stabilisation of the centre wavelength of the light source, with the time constant of the control unit being lower than that of the control unit for regulation of the output power of the light source.

12. A method as claimed in any one of claims 1 to 11, characterised in that Peltier elements are employed for control and stabilisation of the temperature of the light source.

13. A method as claimed in any one of claims 1 to 12, characterised in that the beam of light employed for measurement and control is advanced to the wavelength-selective filter via a polarisation filter and a quarter wave plate.

14. A method as claimed in any one of claims 1 to 13 for measurement of the half-wave voltage and/or the waveguide attenuation of an integrated optical phase modulator, in which the integrated optical phase modulator to be measured is placed in the beam instead of or in addition to the Fabry-Perot interferometer, or in place of the integrated optical phase modulator employed as one, and an alterable voltage is applied to the electrodes thereof, with the phase modulator to be measured being arranged in a parallel, partial beam or in the forwardly emitted beam and penetrated thereby in the case of supplementary laser wavelength regulation by means of the Fabry-Perot interferometer or the phase modulator being employed as a Fabry-Perot interferometer.

15. A method of stabilising the wavelengths and regulating the output power of a semiconductor light source substantially as described herein with reference to the drawings.

16. An apparatus for carrying out the method as claimed in any one of the preceding claims.

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